Ampère's Electrodynamic Molecular Model

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1. Coulomb and the impossibility of electromagnetism

In the eighteenth century, the study of electricity and magnetism became integral parts of the general structure of science. The Newtonian focus upon the strange attractive power of gravitational masses tended to direct attention towards other manifestations of attraction with the hope that some light might be thrown upon the mechanism of attraction in general. As the investigation of magnets and electrically charged bodies progressed, two separate, but very similar, theories were gradually constructed which could explain the observed magnetic and electrical effects. Both magnetism and electricity could be viewed as the result of the action of imponderable fluids upon one another. Thus, a magnet contained an austral and a boreal fluid so dispersed throughout the body of the magnet that the austral fluid was at its densest at the south end, and the boreal at the north end. The particles of each fluid were mutually repellent, whereas particles of opposite sign attracted one another. Similarly, electric phenomena could be reduced to the action of a positive and negative electric fluid in which particles of the same charge repelled one another. There were two rather disquieting aspects of these theories. The action of the particles of the imponderables was at a distance, and the mechanism of this action remained as mysterious in 1800 as it had in Newton's day. The theories also seemed to multiply entities unnecessarily. Was it really necessary to have separate electric and magnetic fluids? Were there not enough analogies between magnetic and electric action to permit the explanation of both in terms of a common cause? This question became so obtrusive in the 1780's that the Bavarian Academy of Science offered a prize for the best paper on the analogy between electricity and magnetism. The various memoirs were collected together by the Dutch physicist, J. H. van Swinden and published in three volumes[1] in 1784. Van Swinden's conclusion, after an exhaustive study of all the supposed analogies, was that electricity and magnetism were essentially different and separate phenomena. In the course of his analysis, he also suggested that one of the desiderata for both electric and magnetic science was a precise knowledge of the laws of attraction and repulsion by which the respective imponderable fluids worked. This appears to have been the stimulus for Charles Coulomb's classical researches. The wonderful precision and ingenuity with which he attacked the problem by means of his torsion balance is well known. The fact that both electrical and magnetic action followed an inverse square law, differing only in the constants, might seem, at first sight, to support the idea of the essential similarity of electricity and magnetism. But Coulomb, armed with his precise methods of measurement, pursued his quarry into the very depths of the intimate structure of matter itself. Electricity and magnetism, he found, were two fundamentally different things, requiring two different kinds of fluids to explain them. The electric fluids penetrated the intermolecular spaces of bodies and flowed from one body to another under the proper urging. The magnetic fluids, on the other

hand, were always contained within molecules of magnetic substances and could not flow from one molecule to another.[2] Each fluid acted only upon its opposite; the two different kinds of fluids had no effect upon one another. Hence, he concluded, there was only a similarity and not an identity of action of the electric and magnetic fluids.

The precision with which Coulomb had carried out his experiments, the care and caution with which he had examined his results and the congruence of his conclusions with his data and analyses, gave enormous strength to his views. The fact that Coulomb had insisted that interaction between the electrical and magnetic fluids was impossible served, at least in France, to stifle any attempts to discover if such an interaction did, in fact, exist. After Oersted had reported his discovery of this interaction, Ampère explained why it had taken so long. In a letter to his friend, M. Roux-Bordier, the elder, at Geneva, dated Feb. 21, 1821, he wrote:

> You are quite right in saying that it is inconceivable that for twenty years no one tried the action of the voltaic pile upon a magnet. I believe, however, that one can assign a cause for this; it was Coulomb's hypothesis on the nature of magnetic action. People believed this hypothesis was a fact and discarded any idea of an action between electricity and the so-called magnetic wires. . . . Everyone had already decided that [interaction] was impossible.[3]

Ampère was one of those who had decided that interaction could not take place. In 1802, while still a teacher at the *École Centrale* of Bourg, he announced in the syllabus of his course in physics that he would " DEMONSTRATE that electrical and magnetic phenomena were due to *two different fluids* which act independently of one another."[4] Thus in Ampère's own mind the idea of two similar, but basically distinct, fluids was firmly established. In accordance with the ancient principle, like acted only upon like, and other substances, regardless of how similar they might seem, could not be affected.

2. THE VOLTAIC PILE

The science of electricity was immeasurably broadened and deepened in 1800 when Alessandro Volta announced the invention of the pile. Hitherto, electricity had meant merely electrostatics; henceforth, it was to include all the physical and chemical effects of electricity in motion.

Volta had been led to the invention of the pile by a close study and criticism of Luigi Galvani's so-called animal electricity. To Volta, a physicist, it soon became clear that the presence of living tissue had very little to do with the production of galvanic effects. By 1794, Volta had shown, at least to his own satisfaction, that the mere contact of two dissimilar metals was sufficient to create an electrical charge. When the metals were in contact at one point and connected by a fluid or dampened conductor at another, the result was a current. Since Ampère was to depend upon Volta's contact theory of the pile, it is worth examining in some detail.

The first thing that the modern reader must do is to banish from his mind all ideas on the Conservation of Energy. It is true that in 1775 the Parisian Academy of Sciences formally announced that it would no longer consider schemes for perpetual motion machines. This applied, however, only to the perpetual motion of ponderable matter and was merely the official recognition of a principle applied in mechanics as far back as the work of Simon Stevin in the sixteenth

century. There was nothing in eighteenth-century science which militated against the perpetual motion of imponderable matter. Since imponderable fluids were extremely 'subtile', there was no reason why such fluids, once put in motion, should not continue to circulate. This, in any case, seems to have been Volta's idea for in his letter to Sir Joseph Banks, P.R.S., announcing the invention of the pile, he described the motion of the electrical fluid as a *mouvement perpetuel* (Volta's italics).

The mechanism by which the electric fluid was put into motion was never explained in detail by Volta. In 1794 he wrote to a friend:

> What do you think of that so-called animal electricity? As for me, I have been convinced for a long time that the whole action comes from metallic contact with any damp body or with water itself; as a result of this contact, the excess of the electric fluid is pushed forward in the damp body by the metals themselves, more by some less by others (most of all by zinc, almost the least of all by silver); from this non-interrupted contact with the various conductors, there arises a continuous circulation of [the electric] fluid.[5]

The whole effect, then, was due to the mere contact of different kinds of matter, and would appear to be due to the different capacities of bodies for the electric fluid. If a zinc disc and a copper disc, touching one another at a point, are connected by a dampened cloth or paper, a simple mechanical reaction takes place. The zinc contains more of the electrical fluid than does the copper; this fluid, therefore, pours into the copper disc. But, since the copper disc is connected by a conducting substance to the zinc, the fluid keeps right on going back to the zinc where the original situation is restored. The electrical fluid, would continue to circulate as long as the contact remained unbroken. Volta was adamant all his life that mere contact was sufficient to explain the pile. The chemical action, he insisted, was the result, not the cause, of the electric effects. Ampère was to adopt a rather odd compromise between the contact and chemical theories in order to account for the molecular currents which were necessary to his theory of magnetism.

3. Ampère's atomic theory

In 1802, Ampère was appointed professor of physics at the *École Centrale* of Bourg. He offered a course in both experimental physics and chemistry and it was here that his love for the latter science was born. From his early youth, he had had a passion for systematization and classification and the current state of chemistry offered a wide field for his talents. To Ampère, chemistry could only become a science when it was firmly based on sound first principles. Such a basis, he felt, must be a knowledge of the nature of the fundamental particles and their relations to one another. Ampère thus turned his attention to the structure of matter. In 1814, the *Annales de chimie* published his " Letter to Berthollet on the determination of the Proportions in which bodies combine, according to the number and the relative disposition of the molecules of which the integral parts are composed." This was Ampère's first enunciation of his atomic theory.

For philosophical reasons, he rejected Dalton's concept of the atom as a little, solid ball of matter. Ampère had read deeply in the philosophy of Immanuel Kant and had accepted Kant's criticism of atomism. Atoms implied discontinuity, and Kant had insisted that such discontinuity in the physical world was

impossible. Ampère's atoms, therefore, were mere physical points whose main attributes were the attractive and repulsive forces with which they were endowed. Since atoms, as such, had no dimensions of themselves, it took four of them, plus their surrounding force fields, to make a solid particle. Thus, every existing molecule must be composed of at least four atoms. When bodies reacted chemically, however, these molecules could be broken down and recombined and it was this concept which led Ampère to the hypothesis which Avogadro had first enunciated in 1811.

The qualities of bodies were the result of molecular form. Four atoms, arranged in a tetrahedron, would have different properties from an octahedral molecule. Presumably, the size of these molecules would depend upon the relative strengths of the forces surrounding the primitive atoms and this would allow for certain basic differences in atomic structure. Given the forms of molecules, the course of chemical dynamics could be predicted, for the resultant molecules must have regular geometric forms.

> If one tries, for example, to combine tetrahedra and octahedra in such a way that the number of the first is half that of the second, one only finds bizarre forms which exhibit no regularity or proportion between the relative sizes of their different faces. One is forced to conclude that a body, *A*, whose particles have the representative form of the tetrahedron, and a body, *B*, whose particles form octahedra, will not combine in such a way that there are two proportions of *B* to one of *A;* this combination is a simple one to accomplish, however, with two proportions of *A* and one of *B*, since two tetrahedra and one octahedron together form a dodecahedron.[6]

In this account of a purely geometrical atomic model, there was no mention of the other elements of chemical science. In particular, electrical forces which the voltaic pile had shown were of primary importance in chemical reactions were totally missing. Ampère, in 1814, was concerned solely with constructing a model in which the laws of chemical combination could be deduced from geometrical form. This model served as the core around which his later concepts were to be built. The fact that the molecule was a complex structure was essential to these later models in which the problems of electricity and magnetism were central.

In the summer of 1820, Hans Christian Oersted announced to the scientific world that a wire carrying an electric current would cause the deflection of a magnetic needle held near it. Oersted had been looking for this effect for years, convinced that it must exist. He, like Ampère, had been steeped in Kant but, unlike Ampère, accepted the Kantian philosophy completely. When Kant had rejected atomism, he had substituted the two forces of attraction and repulsion as the basis of all material phenomena. From this it followed that all forces of nature were but different manifestations of these underlying forces or *Urkräfte*. Hence, all forces of nature must, by definition, be convertible into one another. Their different manifestations could be explained in terms of the different modes in which the forces worked. The magnetic effect of an electric current, therefore, was to be expected. The actual mechanism of its production was somewhat less easy to explain. Although Oersted's discovery was hailed as one of major importance, his explanation was greeted with a notable lack of enthusiasm. To Oersted, electricity itself was the result of the conflict of the two fundamental forces of matter.

> There are two opposing forces which exist in all bodies and which can never entirely be abstracted from them. Each of these forces has an expansive and repulsive action in the volume which each dominates; but they attract one another and produce a contraction, when they react upon one another. The free action of these forces yields electrical phenomena.(7)

The effect of this conflict on the magnetic particles of the needle was what deflected the needle.

> The electric conflict acts only on the magnetic particles of matter. All non-magnetic bodies are permeable to the electric conflict; but magnetic bodies, or, rather, the magnetic particles of these bodies, oppose resistance to the passage of this conflict, in such a way as to be caught up in the shock of contrary actions.
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> It would appear, from the above facts, that the electric conflict is not restricted to the conducting wire, but that there is a rather large sphere of action around it.
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> One can conclude, beyond this, from the observed facts, that this conflict forms a vortex (tourbillon) around the wire; otherwise, it would be impossible to understand how the same portion of wire which, when placed under the magnetic pole, carries it to the east, when it is above, pushes it to the west.(8)

It must be confessed that this is not very clear. It is extremely difficult to visualize precisely what the electric conflict is and how it works. Furthermore, the vortex surrounding the wire cries out for explanation. What is it a vortex in? If it is matter, then how does the electric conflict put it in motion? If it is simply a rotating force, then how does this arise from the electric conflict?

Ampère never accepted Oersted's views on the mechanism of magnetic deflection, simply because he was able to substitute one of his own. Unfortunately, Ampère never revealed, either in his published papers or in his correspondence, how the idea came to him that magnetism was electricity in motion. It is, I think, possible to reconstruct his ideas here for they seem to follow logically from his views. We know that Ampère was an ardent disciple of Coulomb and fully shared Coulomb's views on the inability of the electric and magnetic fluids to act upon one another. When Oersted's experiment showed conclusively that electricity *did* act upon magnetism, this position appeared untenable. But, there was one significant fact that had not been available to Coulomb and which could make a great difference. Coulomb had proved that no interaction took place between the magnetic fluids and the electric fluids only when the electric fluids were at rest. There had been no voltaic pile available to Coulomb, so that electricity in motion was not examined. Given the principle that only like things affected one another, and the possibility that the supposed effect of electricity upon magnetic bodies might merely be due to the effects of dynamic, rather than static, electricity, the next step in the argument is obvious. Two moving currents of electricity should affect one another in the same way as two magnets. On September 4, 1820, using two voltaic piles and two electric circuits, Ampère showed that current-carrying wires attracted and repelled one another, depending upon the direction of the current. The foundation of his theory had received dramatic experimental confirmation.

With his new concept of the nature of magnetism, Ampère was able to subject the new phenomena to mathematical analysis. The result was the theory of electrodynamics which rightly has been described as a masterpiece. The physics of electrodynamics, however, was not so easily dealt with. An electric current might give magnetic effects, but how precisely did the attractions and repulsions take place? And how, on this hypothesis, could the phenomena of

permanent magnetism be accounted for? There were no signs of an electric current in an ordinary bar magnet, nor did the usual tests for electricity reveal the presence of such a current. Almost immediately after his brilliant intuition of the nature of magnetism, Ampère began to wrestle with this problem.

Ampère's starting point was the nature of the electric current itself. It should be emphasized that, at this time, there was really no evidence to prove that such a thing as a current existed at all. Volta had merely assumed a circulation of the electric fluid but there were men of the stature of Faraday who had doubts on this score. But, argued Ampère, the continuing effects of the voltaic pile implied more than a structural change in the circuit. In order for continuous electrochemical action to take place, something must continually pass between the poles. This something must be the electric fluids, put into motion by the contact of dissimilar bodies.

> . . . when the two bodies or the two systems of bodies between which the electromotive action takes place are put in communication with conducting bodies between which there is not an electromotive action equal and opposite to the first, which would maintain the electrical equilibrium and, consequently, the resulting electrical tensions, these tensions disappear or become very small. . . . But, as nothing else has changed in the arrangement of the bodies between which the electromotive action develops, it cannot be doubted that it continues to act, and since the mutual attraction of the two electricities, measured by the difference of electric tensions which has become nil, or has considerably diminished, can no longer restore equilibrium, it is generally agreed that it [the mutual attraction] continues to push the two electricities in the same direction as before, so that a double current, one of positive electricity, the other of negative electricity, parting in opposite directions from the points where the electromotive action takes place, are reunited in the part of the circuit opposite these points. The currents of which I speak accelerate until the inertia of the electric fluids and the resistance that they meet from even the best conductors equal the electromotive force, after which they continue indefinitely with a constant speed so long as this force has the same intensity.[9]

This somewhat confused passage is a strictly orthodox description of the contact theory of the pile and is notable only because it reveals Ampère's ideas at the very moment when his concept of the identity of electricity and magnetism was born. It should be particularly noted that this way of viewing electricity gives absolutely no clue as to how or why two currents of electricity should affect one another. In short, Ampère is here struggling to account for a new effect with an old theory and is notably unsuccessful. What had to be done was first, to devise a new theory of the electric current, then relate this theory to permanent magnetism and finally to give some mechanism of electric interaction which explained the observed attractions and repulsions of electromagnetism.

The necessity to find a new explanation of the mechanism of the electric current arose out of the nature of the attractive and repulsive forces exhibited by currents. Ampère held, erroneously, that electrostatic forces did not act across a vacuum and presumably he felt that electrostatic forces were transmitted by the contact of contiguous particles. One of his ' proofs ' for the existence of a current is the dissimilarity between electrostatic and electrodynamic attraction.

> . . . two electric currents attract or repel one another in a vacuum as well as in air; this is also contrary to what one observes in the mutual action of two conducting bodies electrified in the ordinary manner.[10]

The problem now was to find some way by which the forces created by the motion of the electric fluids could be transmitted through empty space. Ampère's

solution was to evade the problem as thus stated and fall back upon a concept of some antiquity—namely the existence of a luminiferous ether. One of Ampère's close friends was Augustin Fresnel who, together with Dr. Thomas Young, was struggling to establish the undulatory theory of light. This theory required the universal presence of the ether for the transmission of the vibrations of light and Ampère seized upon this substance and established it at the very centre of his theory. The electric current was now no longer the flow of positive and negative electricity in two different directions, excited by the mere contact of dissimilar metals; it became a complex series of chemical compositions and decompositions in which the ether played a significant and essential role. Ampère supposed the ether to be made of a combination of positive and negative electricity. When the ether is in contact with the elements of a voltaic pile, it decomposes (for some reason that Ampère doesn't specify) and the positive and negative fluids move in opposite directions. This leads to a recomposition of the ether as the portion of negative electricity moving in one direction meets the positive electricity coming the other way. Since all the original conditions remain, a second decomposition occurs, followed by a second recomposition. In this fashion, there is both a movement of the electrical fluids from one point to another, and a series of what might be called chemical vibrations set up in the wire. These vibrations can now be used to account for the observed attractions and repulsions without having to appeal to action at a distance.

> . . . it is difficult not to conclude that attraction and repulsion can be produced by the rapid motion of the two electric fluids passing in opposite directions in the conductor by a series of almost instantaneous decompositions and recompositions. . . . In attributing the attractions and repulsions of the conducting wires to this cause, it is impossible not to admit that the motion of the two electricities in these wires is propagated in the neutral fluid which is formed by their union, and which fills all space. . . . When the movements produced in the surrounding fluids by two small portions of electric currents are mutually in phase [se favorisent mutuellement] there is a resulting tendency for them to approach one another; and when the same motions are opposed to one another, the two small portions of the currents tend to move away from one another, as experiments show.[11]

This transmission of force through the ether did not solve the problem of permanent magnetism. Permanent magnets gave no sign of the vibrations in the ether caused by the combination and separation of the electric fluids which Ampère called the electric current.

Ampère's attack on this problem began by duplicating all the effects of permanent magnets with electric currents. Winding wires into helices which he named solenoids (from the Greek for channel, pipe) he showed that the phenomena of permanent magnetism could be perfectly reproduced. And, since this was the result of currents concentric with the solenoid axis, Ampère simply transferred this scheme to the permanent magnet. If, he argued, a permanent magnet had electrical currents all concentric to the axis of the magnet, then this would account for the observed effects.[12] The difficulty that now arose was how to account physically for the existence of such concentric electrical currents. At first, this seemed to pose no unusual difficulties. In the first memoir on electrodynamics, Ampère wrote:

> I will examine in the other paragraphs of this Memoir and in the next Memoir the mutual interaction of an electric current and the terrestrial globe or a magnet, as well as that of two magnets upon one another, and I will show that they both

> follow the law of the mutual action of two electrical currents that I have just made known. Picture as many electrical currents on the surface and in the interior of a magnet as one can think of lines forming closed curves without cutting one another in planes perpendicular to the axis of the magnet. It seems to me almost impossible, with the resulting coincidence with the facts, to doubt that there are really such currents around the axis of magnets, or rather that magnetization only consists in the operation by which one gives to the particles of steel the ability to produce, through the means of the currents of which we have been speaking, the same electromotive action which is found in the voltaic pile, in the zinc oxide of the mineralogists, in the heated tourmaline, and even in the pile formed of dampened cardboard and discs of a single metal at two different temperatures. In the case of the magnet, this electromotive action being developed between the different particles of a single good conducting body, it can never, as we have shown above, produce any electrical tension, but only a continuous current similar to that of a voltaic pile built in the form of a closed curve. . . .
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> Thus it is that one arrives at the unexpected conclusion, that the phenomena associated with the magnet are produced uniquely by electricity and that there is no other difference between the poles of a magnet than their position in regard to the currents of which the magnet is composed. The south pole is that which is to the right of these currents; the north pole is to the left.[13]

This explanation removed one difficulty while introducing another. The concept of concentric currents enabled Ampère to account for permanent magnetism in terms of the motion of the electric fluids, but the means by which this motion was produced were left noticeably vague. It is impossible to say precisely what Ampère had in mind here for he soon abandoned his hypothesis. It is probable that he viewed the production of an electric current here as analogous to the case of the pile. The mere contact of molecules would seem to be sufficient to produce a current.

The suggestion of concentric currents was severely criticized by Fresnel. In a private note to Ampère, Fresnel pointed out that various consequences deduced from this hypothesis could not be observed in actuality. Thus, for example, it would be expected that a continual current around the axis of an iron magnet should produce the same amount of heat as a current of equal strength parallel to the axis. No heating effects were observed. From this, and other observations, Fresnel concluded that there were no such circular currents. In their place, he suggested and Ampère immediately adopted, the substitution of currents *around* each molecule. Fresnel offered no mechanism for the production of such currents, but did show that they could be made completely equivalent to the concentric currents as far as the production of magnetism was concerned. Furthermore, it could be assumed that such molecular currents, unlike their intermolecular cousins, might not produce heat and other effects of ordinary currents.

The production of these molecular currents posed a really serious problem. Ampère was by now thoroughly convinced not only that magnetism could be explained in terms of electrical currents, but actually *was* electricity in motion. The origin of this motion had to be referred now to the structure of the molecule itself and again Ampère fell back on analogy.

> One can consider each molecule as a small voltaic pile in which the currents, entering by one extremity of the molecule and leaving by the opposite end, come together across the space around the first of these two extremities, thus forming a closed solenoid which, according to what we have said before, cannot exert any action since all these currents are of the same intensity and equidistant before the

> molecule is magnetized. When a current-carrying wire or a magnet acts upon these currents, they are displaced and accumulate in greater number on the side of the molecule towards which they are carried by this action; one can then consider the heterogeneous solenoid which results as an assemblage of partial homogeneous solenoids, of which one is closed and has the intensity of the heterogeneous solenoid at its minimum, and the others are not closed; these latter act by producing two forces that one can consider as emanating from their extremities and identical, in all cases, to those that are attributed to molecules of austral and boreal [magnetic] fluid.(14)

I think it almost impossible to extract from this and other similar ' explanations ' just exactly what Ampère had in mind. It is certainly not the simple billiard ball atom surrounded by a current of electricity which usually is presented as Ampère's electrodynamic molecular model. It is a highly complex structure and mechanism whose essence seems destined to remain obscured by the fog of Ampère's style. Some idea of what Ampère thought was taking place in his model may perhaps be gained by viewing the above description against the background of his other atomic concepts. We know that Ampère viewed the molecule as an assemblage of primary particles surrounded by fields of attractive and repulsive force. The entire molecule was permeated by the luminiferous ether and we may legitimately infer that the molecular currents are produced by the interaction of the material atoms and the ether. That two currents—positive and negative—are produced Ampère made abundantly clear.

> By an electric current I understand a double transport, one of positive electricity moving in the direction which I will call each time by the words electric current, and the other of negative electricity in the opposite direction.(15)

Around the molecule circulate two currents of electricity. Each current *enters* the molecule at one end and *emerges* from the other so that the total picture is that of the lines of force of a spherical magnet. The presence of a magnet causes these currents to shift in relation to one another, giving a basic asymmetry to the molecule which, when aligned with other similarly asymmetrical molecules, produces the observed magnetic effects. The action of these asymmetrical molecules is transmitted through space by means of the ether. The decomposition and recomposition of the ether, which makes up the molecular currents themselves, creates etherial vibrations which result in attractions and repulsions. In this view, all bodies are magnetic but only iron, nickel and cobalt permit the alignment of their molecules so that the effect is not cancelled out by random orientation.

At this point, the suspicion almost inevitably arises that we have gone farther than Ampère himself intended. Surely his acute intellect must have seen the holes in his own scheme. One could then argue that any attempt to make a coherent theory out of his conjectures is doomed to failure simply because Ampère never intended his views to be more than an aid to his mathematical analysis. Thus, his hypotheses are purely *ad hoc*, to be used to surmount a difficulty, and abandoned thereafter. Although the temptation to dismiss Ampère's ideas on the nature of electricity and magnetism is very strong, there is too much evidence to show that he was perfectly sincere in his attempts to build a general theory of matter. In 1821, he used his molecular theory to explain chemical combinations. The molecular currents which were so essential to his theory of magnetism, here played as fundamental a role.(16) Similarly, in 1832,

he utilized his electrodynamic molecules, composed of point-atoms to explain the origin of heat and light. The terms, however fuzzy, of his original conception remained the same.

4. Ampère's theory and electrical discovery

Ampère's electrodynamic theory was almost immediately accepted by his scientific peers. It is doubtful whether many bothered to subject the basic physical concepts upon which the theory was built to a very keen critical scrutiny. For most, the elegance of Ampère's mathematics and the ability of the theory to account for phenomena were sufficient guarantees of its essential truth. Only a very few men, like Faraday, who recognized the clumsiness of the model refused to believe in molecular electrical currents. And, after all, did it really matter? One could take a positivist attitude and insist that since the mathematics neatly summarized the facts of electricity and magnetism, this was all that counted. The molecular model merely allowed one to visualize what was happening in the intimate recesses of matter.

Scientific theories, however, are more than mere summaries of facts. Theories allow one to look for new facts for facts, as such, rarely are noticed unless there is a reason for noticing them. Thus, Ampère's original hypothesis on the nature of magnetism had led him to discover the mutual effects of electrical currents. These effects had existed since 1800, but no theory had led anyone before Ampère to see them. But theories can also blind one to facts. Although everyone is willing to admit in the abstract that all theories in science are only partially true, the temptation is overwhelming once one has committed oneself to a specific theory to patch and cut and tailor observations so that they will fit within the confines of the theory. Thus theories act both as instruments of discovery and as hindrances to it. There is such an apt example in the case of Ampère's theory of the way in which a theory can prevent discovery that it seems fitting to end with it.

In 1824, François Arago discovered a strange effect. If a magnetic needle were freely suspended in the horizontal plane above a non-ferrous metallic disc which could be rotated in a parallel plane, the rotation of the disc produced a rotation of the needle. Arago suggested that the mere act of rotation created magnetism in the disc which then caused the needle to move. The subject was then taken up by John Herschel and Charles Babbage, both mathematical physicists who were enthusiastic supporters of Ampère's views. They set out to determine the conditions under which the observed magnetism was produced or destroyed. When radial slits were cut in the disc, the effect was noticeably reduced. If the slits were filled with a conducting substance different from the material of the disc, the effect was largely restored. When the slits were filled with powdered metal, the effect was not restored. Notice was taken of the fact that only electrical conductors appear to exhibit the effect for " if the electrodynamical theory of magnetism be well founded, it is difficult to conceive how that internal circulation of electricity, which has been regarded as necessary for the production of magnetism, can be excited or maintained in non-conducting bodies ".[17]

According to Babbage and Herschel the effect is one of induced *magnetism* in bodies which do not ordinarily exhibit magnetic properties. Somehow the

rotation of the disc permits the alignment of the electrodynamic molecules to create all the effects of magnetic bodies. The slits simply interfere with this alignment.

> . . . It is obvious that where one or more slits are cut in a metallic plate, over which the pole of a magnet is revolving, that immediate and free communication between particle and particle, on which probably the rapid, and certainly the intense development of magnetism depends, is destroyed. . . .
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> The validity of this reasoning is shown by taking the extreme case in which the substance acted on is in the state of powder. Each particle of this becomes necessarily a feeble magnet, and its north south poles, being at the same distance (almost precisely) from the pole of the magnet, counteract each other's action. The extreme feebleness of their magnetism prevents the particles from affecting each other by induction across the intervals which separate them; so that each acts as an individual, and destroys in great measure its own effect. The moment however a *metallic* i.e., *a magnetic contact* is established between them, their mutual induction acts, and the result is a general development of one polarity in the region adjacent to the magnet; and of the other, feebler and more diffused, in the parts of the mass remote from it.[18]

By how little is immortality missed! Yet Babbage and Herschel's conclusions are consistent and well reasoned. By focusing on Ampère's electrodynamic molecule, they were led to the idea of molecular alignment and from thence to their explanation. The idea of *inter*-molecular induced *electrical* currents never entered their heads.

Surely it is no coincidence that the discovery of electromagnetic induction and of the correct explanation of Arago's wheel was made by Michael Faraday who refused to accept Ampère's electrodynamic molecular model.

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